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TEMPORAL PERSISTENCE IN VERTICAL DISTRIBUTIONS OF SOIL MOISTURE CONTENTS

Ya. A. Pachepsky,* A. K. Guber, and D. Jacques

Abstract

When a field or a small watershed is repeatedly surveyed for soil water content, sites often can be spotted where soil is consistently wetter or consistently dryer than average across the study area. The phenomenon has been called time stability, temporal stability, or temporal persistence in spatial patterns of soil water contents. Relatively less is known about temporal persistence of water content at various depths. The objectives of this work are to demonstrate the temporal persistence in soil water contents measured on a vertical two-dimensional grid, and to propose a technique to use this persistence to remedy the effect of probe malfunctioning on the estimates of the average water content in the layer. Sixty time domain reflectometry (TDR) probes (two rods) were installed along the trench in loamy soil at 12 locations with 50-cm horizontal spacing at five depths (15, 35, 55, 75, and 95 cm). The water content data were incomplete due to malfunctioning of connections in the automated measurement system. When all probes worked, some probes at a given depth consistently showed water contents below average whereas others showed water contents above the average. To quantify the persistence, we computed relative water contents as ratios of individual-probe water contents to average water contents from the same depth. Average relative water contents were used in a technique we proposed to correct estimates of depth-average water contents by accounting for missing data. A numerical experiment showed the efficiency of the proposed technique. Corrections for temporal persistence can be useful in estimating layer-averaged water contents and their uncertainty.

When a field or a small watershed is repeatedly surveyed for soil water content, sites often can be spotted where soil is consistently wetter or consistently dryer than average across the study area. Existence of such sites is important for soil management. It is also important for selection of sites to infer the area-average soil water content to use at coarser scale characterization and simulation, that is, to compare with remote sensing data or establishing field- or catchment-wide antecedent moisture conditions for runoff simulations (Grayson and Western, 1998). The phenomenon has been called time stability, temporal stability, or temporal persistence in spatial patterns of soil water content or in soil water contents. Temporal persistence of water contents at the same depth was documented by Vachaud et al. (1985), Kachanoski and de Jong (1988), Zhang and Berndtsson (1988), Goovaerts and Chiang (1993), Reichardt et al. (1993), and Ferreyra et al. (2002) across areas of various extents.

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Relatively less is known about temporal persistence of water content at various depths. Comegna and Basile (1994) found a time-stable spatial structure for the water content in the top 90 cm of the soil profile. Cassel et al. (2000) observed greater temporal persistence of water content in deep soil layers than in shallow layers under a wheat (*Triticum aestivum* L.) crop. This effect could be attributed to the impact of crop root water uptake. Hupet and Vanclooster (2002) showed a substantial effect of vegetation on spatial and temporal structure in profile soil water distributions. Martinez-Fernandez and Ceballos (2003) did not observe any specific pattern of stability with respect to depth.

Our interest to the temporal persistence in soil water content in soil profile arose from a small-scale study. We had TDR probes positioned along a soil transect at five depths with 50-cm spacing. The data were meant to be used to estimate the time series of the average water content at each depth. Some TDR probes eventually began to malfunction. Averaging data from the remaining probes at a given depth could be an option if no persistent difference had existed between TDR-measured water content in different locations. Should such persistence exist, the malfunctioning of probes with consistently lower than average values would lead to averaging data only from the remaining probes that had water contents consistently higher than the true average. This averaging would lead to overestimation of the average water content at the depth of interest.

The objectives of this note are to demonstrate the temporal persistence in soil water contents measured on a vertical two-dimensional grid, and to propose a technique to use this persistence to remedy the effect of probe malfunctioning on the estimates of the average water content in the layer.

The Dataset

The experimental field was located at Bekkevoort, Belgium, at the bottom of a gentle slope and was covered with a meadow. The soil was classified as Eutric Regosol (Food and Agriculture Organization of the United Nations, 1975). Typically the top 1 m includes three soil horizons: an Ap horizon between 0 and 25 cm, a C1 horizon between 25 and 55 cm, and a C2 horizon between 55 and 100 cm. A trench, 1.2 m deep and 8 m long, was dug at the field site. A dye study revealed the occurrence of many macropores throughout the soil profile (Vanderborght et al., 2000). The grass cover was removed from the experimental area. A plastic sheet covered the side of the trench where equipment was installed. Volumetric water content was measured with TDR. Sixty TDR probes (two rods, 25 cm long, 0.5-cm rod diameter, 2.5-cm rod spacing) were installed along the trench at 12 locations with 50-cm spacing at five depths (15, 35, 55, 75, and 95 cm). The insertion point of the first TDR probe was at 10 cm from the trench reference end. The probe locations on the trench wall, soil horizons observed on the wall, and soil texture are shown in Fig. 1. Soil texture was loam at 15-, 35-, and 55-cm sampling depths, and silty loam at 75- and 95-cm depths.

Time domain reflectometry measurements were done with

Abbreviations: TDR, time domain reflectometry.

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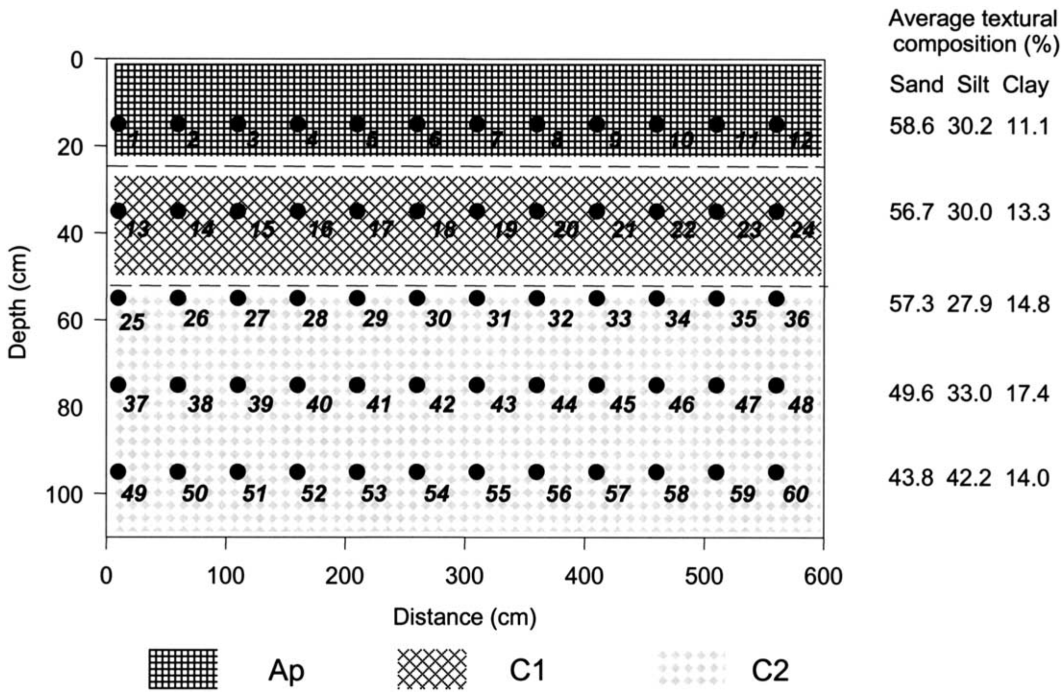

Fig. 1. Time domain reflectometry (TDR) probe locations and numbering. Filled rectangles show Ap, C1, and C2 horizons top to bottom. Dashed lines show the average position of the horizon boundary, and white bands show the observed range of horizon boundary depths. Average values of clay, silt, and sand content are given for the probe installation depths.

a Tektronix (Wilsonville, OR) 1502B cable tester. The automated system of Heimovaara and Bouten (1990) was used to control, retrieve, store, and analyze the measurements of the travel time of an electromagnetic wave along the TDR rods and the soil impedance. Apparent dielectric constants were related to the water content via the site-specific calibration curve (Jacques et al., 1999). One measurement cycle for all TDR probes took approximately 35 min, and time difference between two measurements for the same probe was 2 h. After all devices were installed, the trench was filled. A thin layer of gravel (1–2 cm) was evenly distributed on the study area to (i) decrease the erosive effect of the rain impact on the bare soil surface, (ii) minimize the evaporation from the soil surface, and (iii) decrease the growth of weeds on the experimental plot. Weeds were regularly removed from the site during the summer. Field measurements started on 11 Mar. 1998 (Day 0) and finished on 31 Mar. 1999 (Day 384).

The water content data were incomplete due to malfunctioning of the measurement devices. There also were six 1-d-long, four 2-d-long, and two 5-d-long intervals when the whole measurement system was not working. For the remaining 360 d when the whole measurement system was working, the total number of days when no measurement was made is presented in Table 1 for each probe. The total number of measurements when all 12 probes at the same depth worked was 997, 751, 691, 668, and 768 for 15-, 35-, 55-, 75-, and 95-cm depths, respectively. When removed from soil, all probes were still intact, and were subsequently used in other laboratory or field experiments. The malfunctioning was caused by the connections and switch boxes in the automated measurement system that would stop working properly resulting in missing data for the rest of the experiment for a given probe.

Temporal Persistence in Soil Water Contents

Figure 2 shows measurements made when all probes at the 15-cm depth worked. The water contents reflect the precipitation time series as shown in Fig. 2e. The graphs for the individual probes are clearly shifted relative to each other along the water content axis. This demonstrates the temporal persistence in water contents at different locations. Similar graphs were obtained for other depths (data not shown).

To quantify the persistence, we used an approach similar to the one proposed by Vachaud et al. (1985). The relative water contents β_{ij} for each sampling location i at the same depth for the measurement time j were computed as:

$$\beta_{ij} = \frac{\theta_{ij}}{\overline{\theta}_j} \qquad [1]$$

where θ_{ij} is the water content measured in location i at the jth measurement time, and $\overline{\theta}_j$ is the average water content at the jth measurement time at the depth of interest:

$$\overline{\theta}_j = \frac{1}{N}\sum_{i=1}^{N} \theta_{ij} \qquad [2]$$

where N is the total number of probes at a given depth (N = 12 in our case).

Statistics of β values for all probes are shown in Table 1. Of the 60 total probes, 49 probes had the values of β_{ij} that were larger or less than 1 in more than 95% of cases. This demonstrates that temporal persistence exists in soil profile, and some probes consistently show water contents below average whereas others show water contents above the average. Substantial temporal linear trends in the $\overline{\beta}$ values with coefficients of determination R^2 larger than 0.3 were detected for four probes at the 15-cm depth, and were absent at all other depths.

To test the dependence of the temporal stability on depth, we used values of the standard deviations s_{β_i} of the β_{ij} values. The larger this standard deviation the less temporal stability is observed for the probe i. Inspection of the dependence of s_{β_i} on depth showed that there was a weak inverse relationship (data not shown). The R^2 value of the linear regression of depth vs. of s_{β_i} was 0.202 and differed statistically significantly from zero (p = 0.001).

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Table 1. Statistics of individual time domain reflectometry (TDR) probes.

i†	DND‡	$\overline{\beta}_i$§	CV_i¶
	d		%
1*	131	0.93	2.0
2*	0	1.04	1.2
3	198	1.02	1.2
4*	2	0.85	1.1
5*	8	1.06	1.2
6*	0	0.94	1.9
7*	0	1.06	1.6
8	0	0.95	2.7
9*	0	0.95	1.9
10*	90	1.04	1.1
11*	132	1.09	1.4
12*	61	1.07	2.1
13	114	1.01	1.1
14	0	1.00	0.9
15*	273	1.03	1.3
16*	0	0.96	0.8
17	0	0.99	0.7
18*	0	1.03	0.7
19*	0	0.89	1.1
20*	0	0.95	0.8
21*	0	0.95	1.1
22*	93	1.04	0.6
23*	212	1.07	0.6
24*	61	1.07	0.8
25*	0	0.93	0.9
26	301	0.99	1.0
27*	212	0.96	0.5
28*	0	0.95	0.7
29*	0	1.02	0.7
30	0	1.00	0.7
31	0	1.02	1.5
32*	116	1.02	0.8
33	2	1.01	0.9
34*	2	1.02	0.8
35	127	1.01	2.0
36*	129	1.07	0.8
37*	0	0.93	1.3
38	284	1.01	0.6
39*	0	0.97	0.6
40*	0	0.90	0.6
41*	0	1.05	0.6
42*	0	1.02	0.6
43	0	1.01	0.8
44*	166	1.07	2.4
45	109	1.01	0.6
46*	0	1.03	0.6
47*	60	1.07	0.8
48*	178	0.93	1.2
49*	0	1.03	0.8
50*	254	1.05	1.3
51*	0	1.02	0.7
52*	0	1.02	0.6
53	0	1.00	0.7
54*	0	1.05	0.9
55*	0	0.84	1.3
56*	42	1.02	0.8
57	41	1.01	0.8
58	1	1.00	0.7
59*	62	1.02	0.6
60*	130	0.96	0.9

* Probes marked with the asterisk showed water contents that were different from the depth-average water contents in more than 95% of cases.
† Probe number i according to Fig. 1.
‡ Total number of days with no data.
§ Mean ratio of the probe i water contents to the depth-average water contents. Values were computed from hourly data.
¶ Coefficient of variation of the ratios of the probe i water content to the depth-average water contents. Values were computed from hourly data.

Correcting the Average Water Content for the Persistence

Assume that K probes of total N are working at one depth. The average water content over working probes at this depth for the sampling time j is:

$$\hat{\theta}_j = \frac{1}{K}\sum_{i=1}^{K}\theta_{ij} \qquad [3]$$

The true average water content is:

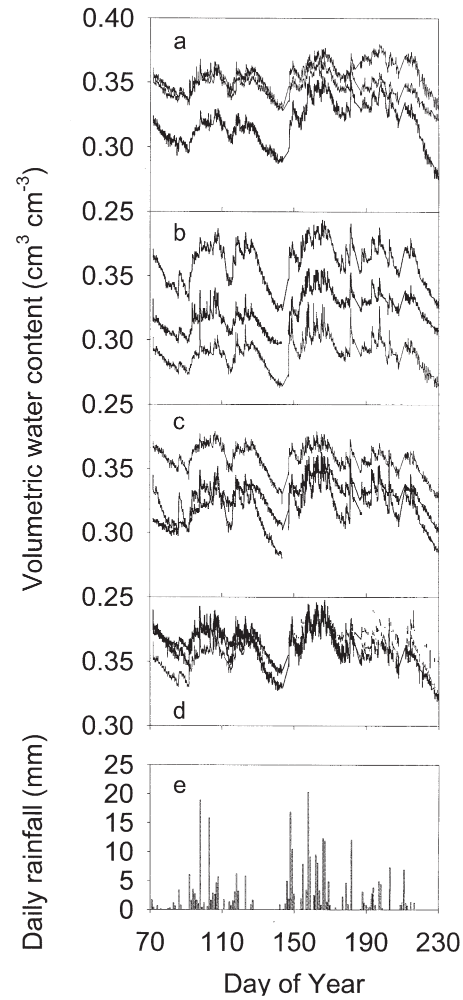

Fig. 2. Time series of time domain reflectometry (TDR)–measured water contents at the 15-cm depth (a–d) and precipitation (e) during the period when all probes worked at this depth. Probe numbers top to bottom: (a) 2, 3, 1; (b) 5, 6, 4; (c) 7, 8, 9; and (d) 11, 12, 10. Probe numbering is shown in Fig. 1.

$$\overline{\theta}_j = \frac{1}{N}\left(\sum_{i=1}^{K}\theta_{ij} + \sum_{i=K+1}^{N}\theta_{ij}\right) \qquad [4]$$

where the first term in parentheses includes data from measurements, and the second includes unknown values that would come from malfunctioning probes should they work. The idea of the technique is to replace the unknown values with their estimates. The estimation consists of replacing the actual value of β_{ij} with the average value of β_{ij} over the period when all probes had worked, $\overline{\beta}_i$:

$$\theta_{ij} \approx \overline{\theta}_j\overline{\beta}_i \qquad [5]$$

where i denotes a number of malfunctioning probes ($i = K + 1, K + 2, ..., N$). Values of $\overline{\beta}_i$ are given in Table 1.

Substituting θ_{ij} from Eq. [5] into Eq. [4] and using Eq. [3], one has:

$$\overline{\theta}_j \approx \frac{1}{N}\left(K\hat{\theta}_j + \overline{\theta}_j\sum_{i=K+1}^{N}\overline{\beta}_i\right) \qquad [6]$$

Rearranging Eq. [6] leads to:

$$\overline{\theta}_j \approx \frac{K\hat{\theta}_j}{N - \sum_{i=K+1}^{N}\overline{\beta}_i} \qquad [7]$$

The sum of $\overline{\beta}_i$ values is always equal to N because

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$\sum_{i=1}^{N}\beta_{ij} = \frac{\sum_{i=1}^{N}\theta_{ij}}{\theta_j} = \frac{N\overline{\theta}_j}{\overline{\theta}_j} = N$ for any j. Therefore the denominator in the Eq. [7] is equal to $\sum_{i=1}^{K}\overline{\beta}_i$. This leads to the following equation to estimate $\overline{\theta}_j$ by correcting $\hat{\theta}_j$:

$$\overline{\theta}_j \approx \frac{K\hat{\theta}_j}{\sum_{i=1}^{K}\overline{\beta}_i} \quad [8]$$

Only measured values are included in this equation.

To test the correction technique based on Eq. [8], we performed simulation experiments. We used all hourly measurements over the period when all 12 probes worked at the 15-cm depth. First, we computed values of $\overline{\beta}_i$ and values $\overline{\theta}_j$. The latter were dubbed "true average water contents." Then we randomly removed several probes for each sampling time and estimated the average water content using two methods: (i) the average water content over remaining probes assumed to be working in simulations (i.e., $\hat{\theta}_j$ according Eq. [3]), and (ii) the corrected value of the average water content according to Eq. [8]. We removed up to eight probes in Experiment I (Fig. 3a and 3b), up to four probes in Experiment II (Fig. 3c and 3d), and one or two probes in Experiment III. As expected, as less probes are removed, the average water content over working probes is a better estimate of the true average (Fig. 3a, 3c, and 3e). Correction according to Eq. [8] consistently gave a much better estimate of the true average $\overline{\theta}_j$ than the average over working probes $\hat{\theta}_j$. The improvement with Eq. [8] depended on the total number of working probes. The smaller the number of working probes the more efficient was the correction.

When the correction with Eq. [8] was applied to actual measured water contents during the whole observation period of 360 d, it made substantial changes in some of the estimated

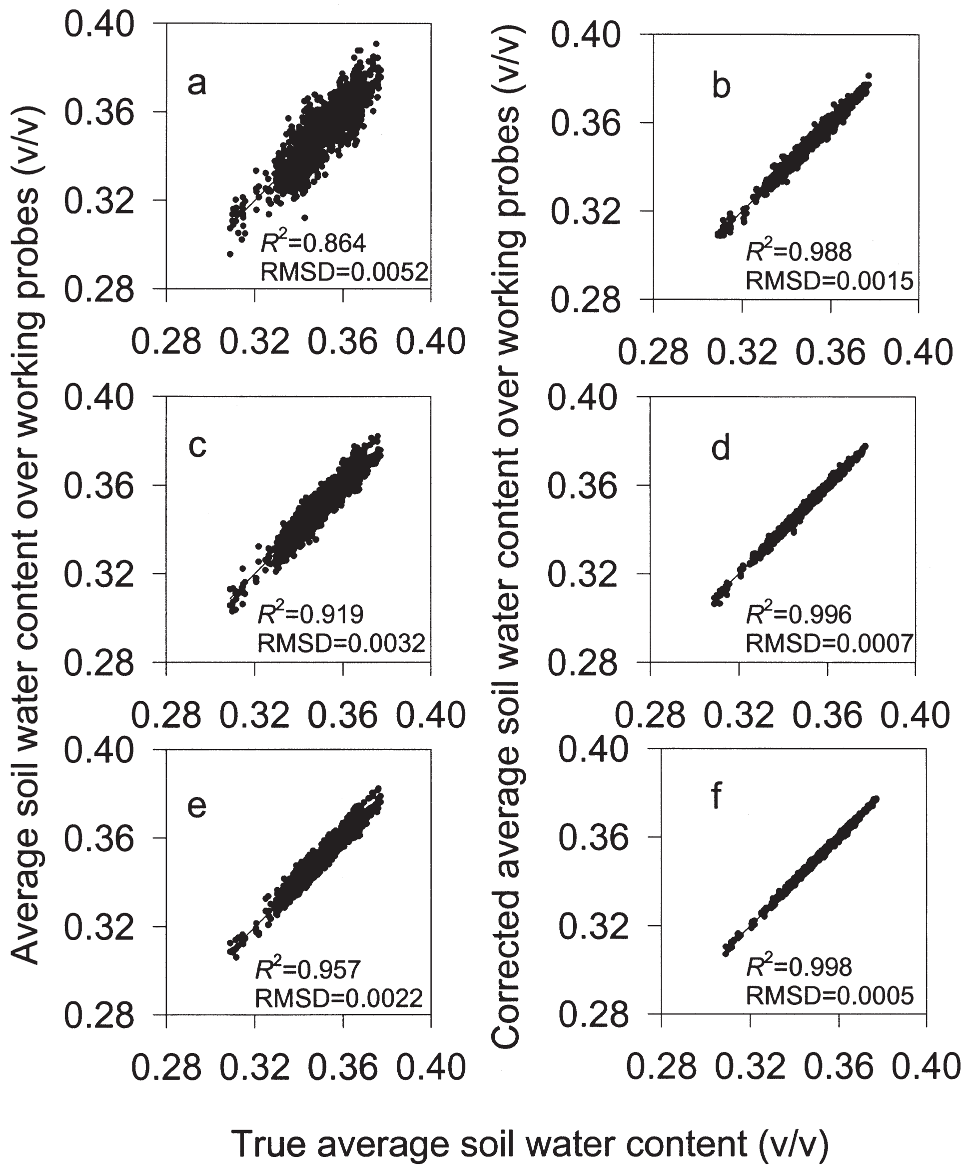

Fig. 3. Simulated effect of the correction for temporal persistence on the relationship between actual and estimated layer-average water contents at the 15-cm depth. Number of probes removed: (a, b) from one to eight; (c, d) from one to four; (e, f) from one to two. Average water content over remaining probes before (a, c, e) and after (b, d, f) the correction application. Values of R^2 are the determination coefficients and RSMD is the root-mean square differences of the linear regression actual vs. estimated average water contents.

layer-average water contents. Maximum values for the corrections of the average layer-average water contents were 0.016, 0.013, 0.008, 0.014, and 0.014 v/v at the depths of 15, 3, 55, 75, and 95 cm, respectively. Ranges of observed layer-average water contents $\hat{\theta}_j$ at the same depths were 0.089, 0.062, 0.037, 0.046, and 0.040 v/v, respectively. The corrections were relatively more important at larger depths because of narrower ranges of observed water contents.

Discussion

The temporal persistence in water regimes was well-expressed at all five studied depths (Fig. 2 and Table 1). Texture, organic matter contents, soil structure, and the number of channels formed by roots, worms, and other organisms were mentioned as leading static factors that affect spatial variations of soil water contents (Reynolds, 1970). Vachaud et al. (1985) related the variability of soil water contents and persistence in soil water content distributions to the variations in soil texture. These considerations could be pertinent to this work, although we do not have direct data to pinpoint the specific source of the persistence. In our research area, a study of water retention along a 30-m trench in the same soil at the adjacent site (Mallants et al., 1996) showed substantial small-scale variability. Data on saturated volumetric water content θ_s from this work are shown in Fig. 4. Values of θ_s were measured in 5-cm-long and 5.1-cm-diameter cores (i.e., at the scale comparable with the scale of TDR measurements). The variability of saturated water contents is comparable with variability in measured water content, indicating that the variations in water contents measured with TDR are realistic. We hypothesized that differences in soil structure can be responsible for those variations. The dependence of water retention on size of soil aggregates has been demonstrated in several studies, for example, Wittmuss and Mazurak (1958), Tamboli et al. (1964), Amemiya (1965), Chang (1968), and Guber et al. (2003). Such dependence can cause differences in water contents at the same depth if soil matric potentials do not vary much across locations at this depth. This might contribute to the temporal persistence in water contents that we observed.

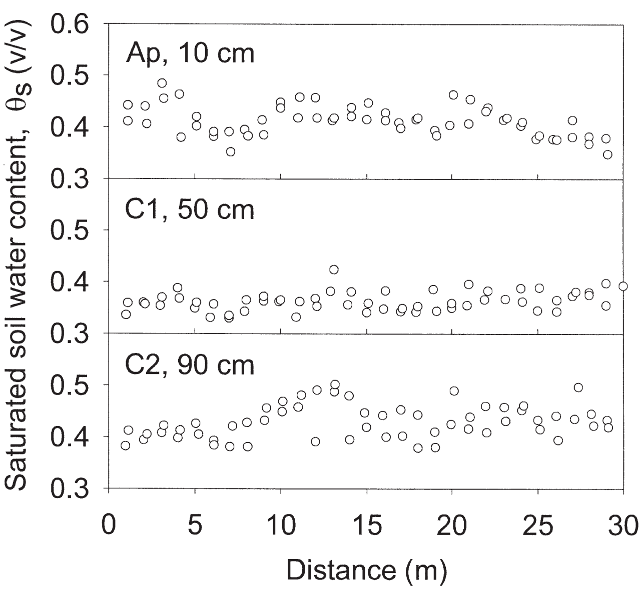

Fig. 4. Saturated soil water content measured at the adjacent site along the 30-m-long transect at three depths (adapted from Mallants et al., 1996).

The proposed approach relies on the temporal persistence. Alternatively, one could try to estimate data for the malfunctioning probes using an interpolation technique, for example using kriging as suggested in spatio-temporal geostatistics (Christakos, 2000). We made an attempt to apply it, and found unsatisfactory results for probes positioned close to the corners of the spatiotemporal domain.

The proposed correction techniques worked reasonably well, mostly because the probability distribution functions of relative water contents were narrow, and the average relative water content was a good approximation for the whole distribution. The wider the distribution the less persistence is observed, and the less useful the proposed correction can be. Temporal trends in values of relative water contents make their distributions wider. Significant temporal trends were observed only for four probes at the 15-cm depth. This corresponds to the conclusion of Cassel et al. (2000) about higher persistence in deeper horizons. These authors attributed such dependence on depth to the root activity. Plant roots were not active in this work. The weakest time persistence at the shallowest observation depth in this work seemed to be more in line with results of Zhang and Berndtsson (1988) and Hupet and Vanclooster (2002), who had documented weaker temporal persistence during dry periods compared with wet ones.

Temporal persistence provides an opportunity to decrease the uncertainty of estimates of spatially averaged water contents. Indeed, if probe readings at a given depth are thought to be independent random values at any measurement time, the differences between those readings will be incorporated in the standard deviation of the average water content at this depth. However, in case of persistence, the individual probe readings are not independent. Therefore, only the variability of relative water contents has to be included in the estimate of the variability of the average soil water content. The variability of relative water contents is much smaller than variability of individual probe readings. Consequently, much smaller values of the standard deviation of the average water content should be expected. One effect of that is an improvement in accuracy of soil water balance computed using average soil water contents at several depths, because the average water contents will be less uncertain (will have smaller variability estimates) if temporal persistence in soil water content distributions is present and taken into account. Another advantage of establishing the temporal persistence in soil water content distributions is allowing removal of some of the probes and having their measurements reconstructed from remaining probes. The temporal persistence means a temporal stability of spatial variability in soil water contents that may be useful in estimating uncertainty of measurements with a small number of probes. Correct treatments of those topics are outside of the scope of

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this note, but they seem to be important enough to be explored.

In summary, the temporal persistence of water content patterns in soil profiles has been observed at a small scale. A correction using temporal persistence has been suggested that can be important in estimating layer-averaged water contents and their uncertainty in cases of temporary malfunctioning equipment.

Acknowledgments

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